CIRCE, the Proposed Coherent InfraRed Center at the Lawrence Berkeley National Laboratory

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At the Advanced Light Source (ALS) of the Lawrence Berkeley National Laboratory (LBNL), we are proposing the construction of CIRCE (Coherent InfraRed Center), a ring-based photon source completely optimized for the generation of coherent synchrotron radiation (CSR) in the terahertz frequency range [1]. CIRCE exploits the full complement of the CSR-production mechanisms presently available for obtaining top performance, including a photon flux exceeding by more than nine orders of magnitude that of existing "conventional" broadband terahertz sources.

Interest in science using radiation in this frequency range is rapidly increasing. A recent workshop in the terahertz scientific community, organized by three major U.S. federal funding agencies [2], emphasized the potential for top-quality science that breakthrough terahertz sources would enable. The scientific fields that would benefit range from solid-state physics (semiconductors, metals, superconductors, strongly correlated materials, etc.) through chemistry and biology and on to applications in medical science and security. A major problem is that generating radiation of significant intensity in this frequency range, which lies between microwaves and infrared, is not straightforward. Indeed, because of the lack of sources, this region is often referred to as the "terahertz gap". CSR-based sources are very promising candidates for filling this gap.

Coherent synchrotron radiation occurs when the synchrotron emission from the relativistic electrons in a beam bunch is in phase. Such a situation is achieved when the length of an electron bunch is comparable with or shorter than the wavelength of the radiation being emitted. At 1 THz, this wavelength is about 300 μm. In the coherent regime, the radiation intensity is proportional to the square of the number of particles per bunch, in contrast to the linear dependence of conventional incoherent synchrotron radiation. Considering that the number of electrons per bunch in a storage ring is typically very large ($10^6 \div 10^{11}$), the potential intensity gain for a CSR source is huge. Achievable bunch lengths and the shielding effect of the conductive vacuum chamber in storage rings confine the possibility of generating CSR to the terahertz frequency range (wavelengths from about 100 μm to few millimeters).

A comprehensive historical review of the work done on coherent synchrotron radiation in storage rings can be found in reference [3]. Although CSR was predicted to occur in high energy storage rings over a half-century ago [4, 5], it is only in the past few years that the first observations have occurred. Intense bursts of coherent synchrotron radiation with a stochastic character have been measured in the terahertz frequency range in storage rings at several synchrotron light sources [6-12]. The work from groups at the Stanford Linear Accelerator Center (SLAC), at LBNL, and at the Berliner Elektronenspeicherring-Gesellschaft für Synchrotron Strahlung (BESSY) [12-15] showed that this bursting emission of CSR is associated with a single bunch instability. Usually referred to as the microbunching instability (MBI), this instability is driven by the fields of the synchrotron radiation (SR) emitted by the bunch itself. Although interesting from the accelerator physics point of view, these bursts of CSR are not very useful as a terahertz source, owing to their intrinsically unstable and stochastic nature.

CSR emission was observed with remarkably different characteristics at BESSY when the storage ring was tuned to a special mode for short bunches [16, 17]. In fact, the emitted radiation was not the quasi-random bursting previously observed, but a powerful and stable flux of broadband CSR in the terahertz range, exactly what is required for a source that is useful for scientific experiments. Collaboration between the same LBNL, SLAC and BESSY groups produced a model which reproduces the observations and which can be used for designing a ring-based source optimized for the generation of stable terahertz CSR [18].

One of the interesting features of the CSR spectra measured at BESSY is that they extend to significantly shorter wavelengths than the ones expected from a Gaussian longitudinal distribution of the bunch. The developed showed that the SR fields can produce, under the correct circumstances, a stable distortion of the bunch distribution from Gaussian towards a saw-tooth like shape with a sharp leading edge. This stable distortion was ultimately responsible for the observed extension of the CSR spectra towards shorter wavelengths in BESSY. In what follows, we will refer to this configuration as the "ultra-stable" mode of operation.

Another recent CSR development in storage rings was the one that was first demonstrated at the ALS and more recently also at BESSY by means of the so-called "femtoslicing" technique [19-22] [Also see *CERN Courier*, July/August 2000, pp. 31-32]. In the femtoslicing scheme, the co-propagation of a femtosecond optical laser pulse with a much longer electron bunch in a wiggler generates a modulation of the electron energy in a femtosecond slice of the bunch. When the bunch propagates in a dispersive region, the energy-modulated particles are transversely displaced. By a proper masking of the SR, the part emitted by the core of the bunch can be now removed while still allowing the transmission of the SR part emitted by the displaced electrons. In this way, femtosecond x-ray pulses are obtained.

At the same time, because of the longitudinal dispersion in the ring, the modulation in energy induces a density variation in the longitudinal distribution as the bunch propagates along the ring. The characteristic length of these longitudinal structures starts from tens of micrometers (few tens of femtoseconds duration) immediately after the laser-beam interaction region in the wiggler, quickly increases up to the order of a millimeter, and finally disappears in a few ring turns. These structures radiate intense CSR in the terahertz frequency range with appealing characteristics: very short CSR pulses (of the same order as the laser pulse length) which extends the CSR spectrum towards shorter wavelengths (to about 10 μm or about 30 THz) than those in the previously described ultra-stable mode, high energies per THz pulse (tens of μJ), and THz CSR pulses intrinsically synchronous with the femtosecond laser and x-ray pulses (allowing for a variety of pump–probe experiments and/or electro-optic sampling techniques). The main limitation is the relatively low repetition rate (few kHz), which is imposed by the present laser technology.

In designing the CIRCE ring we have made provisions for optimized versions of all the above-described techniques for the generation of terahertz CSR. Figure 1 shows a 3D layout of the CIRCE ring inside the ALS facility. The new ring, 66 m in circumference and operating at 600 MeV, is designed to be located on top of the ALS Booster Ring shielding and will share the injector with the ALS storage ring.

Figure 2 shows the impressive flux of CIRCE calculated for three different settings of the ultra-stable mode of operation. The gain of many orders of magnitude in the terahertz frequency range over the existing “conventional” source is clearly visible. In Figure 3, we show how the femtoslicing mode nicely complements the ultra-stable mode of operation in CIRCE. In fact, the calculated spectra for the two modes together cover the entire terahertz range from wavelengths of about 10 μm (30 THz) to about 10 mm (0.03 THz). The energy per THz pulse in the example used for the femtoslicing case is about 8.5 μJ which when focused onto a sample would provide an electric field of about 10^6 V/cm. The present laser technology should allow repetition rates as high as 10 ÷ 100 KHz.

The vacuum chambers in the dipole magnets and the first in-vacuum mirror have been specially designed for efficient collection of terahertz synchrotron radiation. The design calls for three ports with 100-mrad horizontal by 140-mrad vertical acceptance for each of the 12 dipole magnets, giving a potential total of 36 dipole beamlines in CIRCE. The ring lay-out also includes six 3.5-m straight sections that can be used for insertion devices for future possible sources (as for the case of the wiggler in the femtoslicing scheme).

At the present time, we have completed a detailed feasibility study of CIRCE that includes electron beam linear and nonlinear dynamics studies, magnetic design of all the magnets, design of the special high-acceptance dipole vacuum chamber, and evaluation of the compatibility of CIRCE with the ALS facility. In addition, we have experimentally investigated the issue of possible resonating modes that could be excited by the electron beam in the high-acceptance dipole vacuum chamber. These modes, potentially dangerous for the electron beam stability, have been measured and characterized by means of radio-frequency measurements in a prototype dipole chamber. No “show stoppers” have been identified and CIRCE is part of the current five years strategic plan for the ALS.

For additional information about CIRCE, please visit: http://CIRCE.lbl.gov/.

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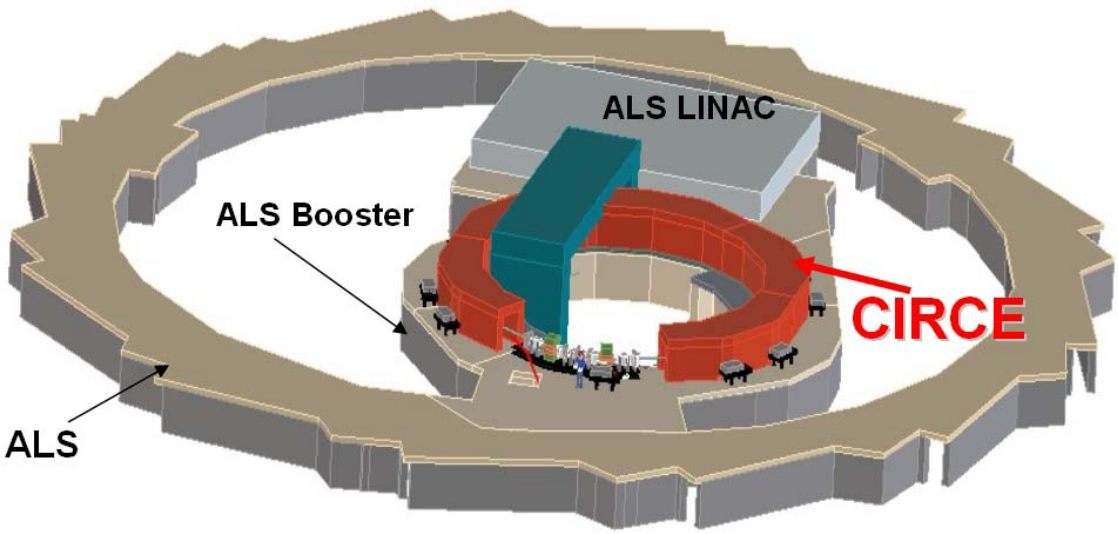

Figure 1. The CIRCE ring in the ALS complex.

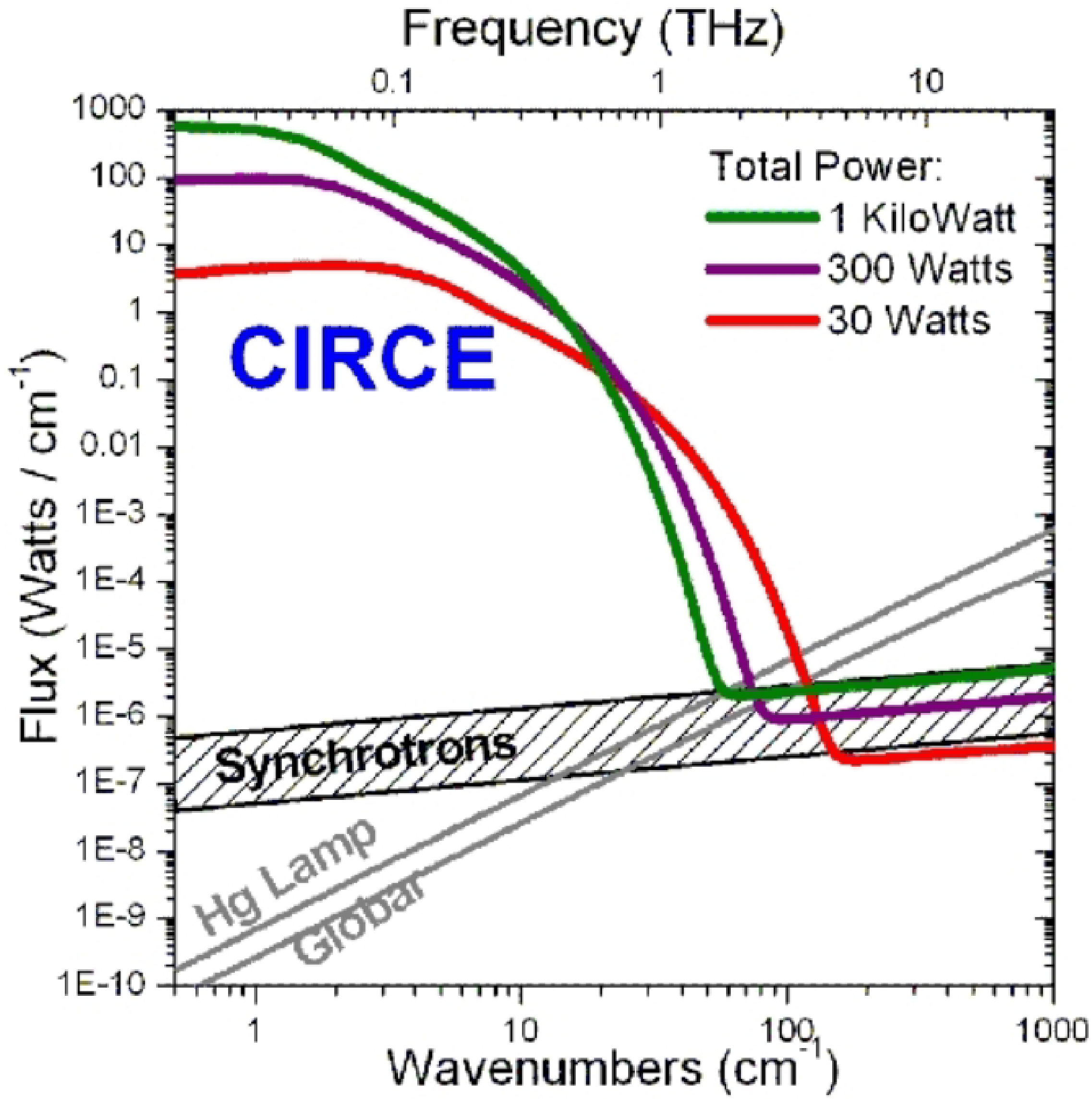

Figure 2. Flux calculations for CIRCE in the ultra-stable mode of operation compared with conventional synchrotron and thermal far-IR sources (1 wavenumber = $1/\lambda$). The three CIRCE curves, for three different ultra-stable sets, demonstrate how the CIRCE source can be tuned for high power (green curve), for extending coherent emission to shorter wavelengths (red curve), or somewhere in between (such as the purple curve).

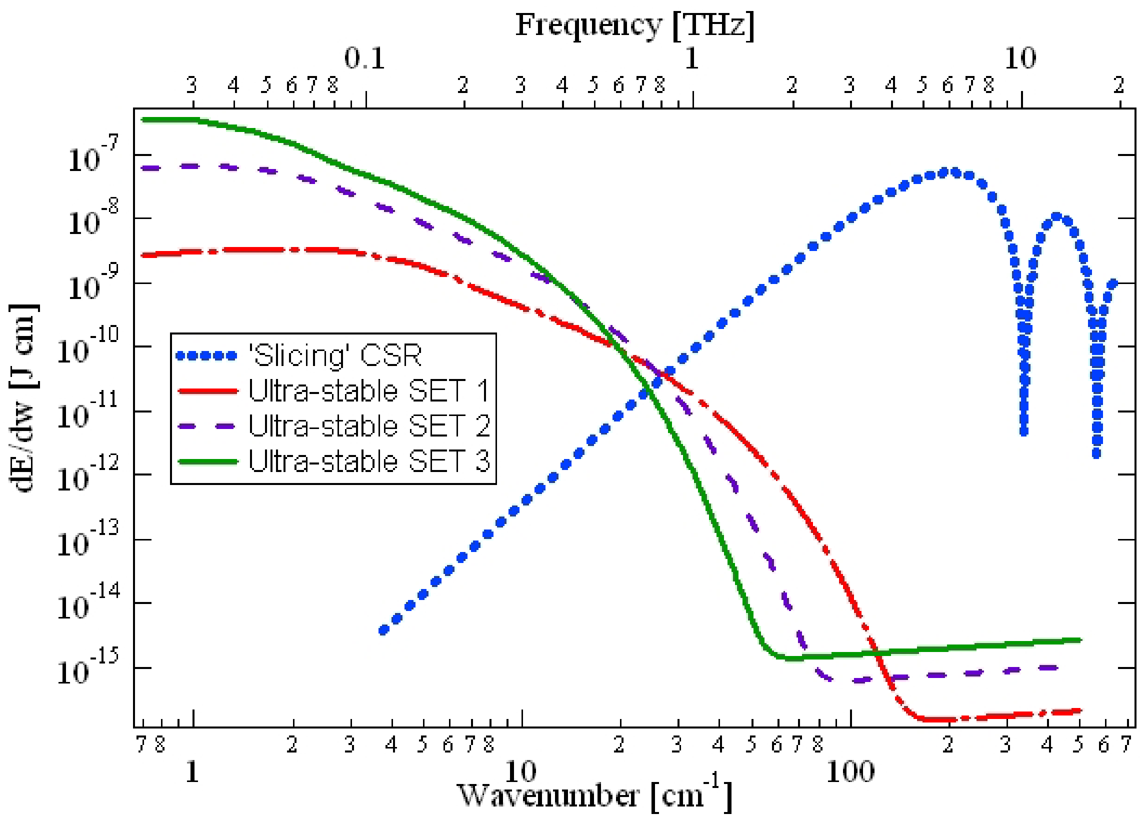

Figure 3. Calculation of the energy per pulse per wavenumber for CIRCE in three sets of the ultra-stable mode and for an example of the femtoslicing mode of operation (wavenumber = $1/\lambda$).